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"Respiratory Plasticity Following Spinal Injury: Role of Chloride-Dependent Inhibitory Neurotransmission"

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14. ABSTRACT

Our fundamental goal is to test the hypothesis that spontaneous and induced plasticity in chloride-dependent synaptic inhibition of phrenic motor neurons contributes to functional recovery from chronic cervical spinal contusion (CSC) injuries. In the last two years, we performed experiments to test the hypothesis that CSC and repetitive acute intermittent hypoxia (rAIH) shift the NKCC1/KCC2 balance in phrenic motor neurons, degrading (CSC) and restoring (rAIH) chloride-dependent synaptic inhibition, and began experiments investigating the role of spinal PKCζ in spontaneous recovery of breathing following CSC. Our analyses indicate that CSC increases membrane NKCC1, and decreases the membrane-cytosol KCC2 ratio, consistent with the interpretation that compensatory shifts in NKCC1/KCC2 balance in phrenic motor neurons preserves respiratory function following CSC. rAIH had no apparent effects on either protein. Preliminary studies also suggest that spontaneous recovery of diaphragm EMG and breathing capacity occurs within the first 3 days following injury by a spinal PKCζ-dependent mechanism. In the final months of this no cost extension, we plan to: 1) prepare a manuscript for publication concerning immunofluorescence results, and 2) complete experiments concerning the role of PKCζ in spontaneous ventilatory compensation in unanesthetized rats.

15. SUBJECT TERMS

Spinal Injury, Treatment, Intermittent hypoxia, rats, spontaneous recovery, induced recovery, rAIH, PKCζ, TrkB, contusion

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Progress report:
Award Number W81XWH-13-1-0410
"Respiratory Plasticity Following Spinal Injury: Role of Chloride-Dependent Inhibitory Neurotransmission"
Research Completed at University of Wisconsin, Madison and University of Florida

INTRODUCTION

Our fundamental goal is to test the hypothesis that spontaneous and induced plasticity in chloride-dependent synaptic inhibition of phrenic motor neurons contributes to functional recovery from chronic cervical spinal contusion (CSC) injuries. In this project period, we tested the specific hypothesis that CSC and repetitive acute intermittent hypoxia (rAIH) shift the NKCC1/KCC2 balance in phrenic motor neurons, degrading (CSC) and restoring (rAIH) chloride-dependent synaptic inhibition.

SPECIFIC AIMS

Aim 1: Test the hypothesis that midline C4 cervical spinal contusions (CSC) degrade chloride-dependent inhibitory synaptic transmission in phrenic motor neurons by an atypical PKC-dependent mechanism, contributing to spontaneous functional recovery of breathing capacity.

a. *Does CSC differentially alter membrane expression of the chloride co-transporters NKCC1 and KCC2 in the phrenic motor nucleus?*
b. *Does CSC decrease GABAA receptor-induced inhibition of phrenic motor output?*
c. *Is CSC-induced attenuation of chloride-dependent synaptic inhibition PKCzeta dependent?*
d. *Is spinal PKCzeta required for spontaneous recovery of breathing capacity following CSC?*

Aim 2: Test the hypothesis that repetitive acute intermittent hypoxia (rAIH) normalizes chloride-dependent inhibitory synaptic transmission in phrenic motor neurons by a TrkB-dependent mechanism.

a. *Does rAIH normalize membrane NKCC1/KCC2 expression in the phrenic motor nucleus?*
b. *Does rAIH normalize GABAA receptor-induced inhibition of phrenic motor output?*
c. *Does rAIH-induced normalization of chloride-dependent synaptic inhibition require TrkB activity?*

OVERALL PROJECT SUMMARY

Specific Aims 1a and 2a: rAIH (repetitive acute intermittent hypoxia) normalizes shifts in membrane NKCC1 and KCC2 in the phrenic motor pool caused by C4 cervical spinal contusions (CSC).

Task 1: Complete administrative requirements (ACURO)

Current Status: Completed in the first reporting period (9/4/13)

Task 2: Quantify changes in membrane NKCC1 and KCC2 in the phrenic motor nucleus following cervical contusion injuries in rats exposed to rAIH or room air.

Subtask 2a. Perform spinal injuries and sham surgeries

Current Status: Completed in the first reporting period.

Subtask 2c. Perfuse subset of rats from subtask 2b 5 wks post-surgery and quantify changes in NKCC1/KCC2 using immunofluorescence.

Current Status: Completed in the first reporting period.

Subtask 2d. Harvest spinal cords from a subset of rats from subtask 2b 5 wks post-surgery to quantify NKCC1/KCC2 with surface biotinylation and immunoblots.

Current Status: 90% complete; quantitative analysis of tissues is ongoing, will be completed by 9/1/16. Results to date detailed below.

Sham surgeries and left lateral C3 contusion injuries (CSC; 135 kD) were successfully performed on 24 rats; these rats were divided into the following groups: a) normoxia + sham surgery; b) normoxia + CSC; c) rAIH + sham surgery; and d) rAIH + CSC. rAIH was initiated one week-post CSC, and consisted of 10 AIH episodes per day, 3x per week for 4 weeks). After immunofluoresence for KCC1/NKCC2, confocal z-stacks of cholera-toxin back-labeled phrenic motor neurons were made ipsilateral and contralateral to injury. A semi-automated quantification algorithm implemented in MATLAB (developed this past reporting period) was used to assess membrane and cytosolic NKCC1 and KCC2 immunofluoresence in identified phrenic motor neurons. A three-way MANOVA and Tukey's *post hoc* test were performed. We found: a) NKCC1 increased in cell membranes and decreased in the cytosol of phrenic motor neurons after CSC, both ipsi- and contralateral to injury ($p<0.05$), b) membrane KCC2 non-significantly decreased following injury ($p = 0.07$); membrane to cytosolic ratio decreased post-CSC ($p<0.05$). rAIH had no significant effects on NKCC1 or KCC2 ($p>0.05$). Collectively, these data are consistent with the hypothesis that inhibitory neurotransmission is decreased following CSC.

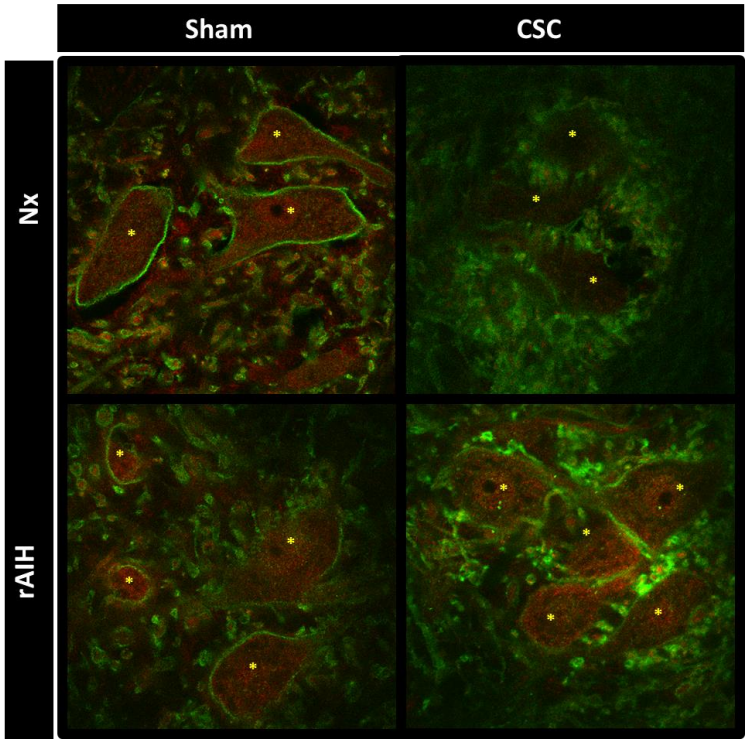

Figure 1: Immunofluoresence of NKCC1 (red), KCC2 (green) in C4 phrenic motor neurons in normoxia and rAIH treated rats with and without CSC. All micrographs are at 100X magnification. KCC2 is highly localized on phrenic motor neuron (indicated by small white asterisk; CtB was turned off in these micrographs to emphasize target proteins) membranes. CSC reduced KCC2 membrane expression, which was marginally significantly different from sham rats ($p=0.07$). NKCC1 significantly increased in the membrane, and decreased in the cytosol, following CSC ($p<0.05$). rAIH had no additional effect on KCC2 or NKCC1.

Specific Aims 1b and 2b: rAIH restores CSC-induced loss of GABAA receptor-induced inhibition of phrenic motor output.

Task 3: Quantify GABAA receptor-induced inhibition of phrenic motor output with pressure microinjections of muscimol following cervical injuries in rats exposed to rAIH or room air.

Subtask 3a. Perform cervical contusion injuries and sham surgeries.

Current Status: Completed in the first reporting period.

Subtask 3b. Expose rats to rAIH or room air beginning 1 week post-surgery.

Current Status: Completed in the first reporting period.

Subtask 3c. Quantify phrenic responses to pressure microinjections of muscimol into phrenic nucleus 5 wks post-surgery.

Current Status: Completed in this reporting period. Results summarized below.

Rats were urethane-anesthetized, ventilated, paralyzed and the phrenic nerve isolated for recording. Muscimol (GABAA receptor agonist) was injected into the intrathecal space of the cervical spinal cord to assess the potency of chloride-dependent synaptic inhibition in rats 5 weeks post- CSC or sham surgery, with and without rAIH (n=8-9 per group, 4 groups; 34 rats total; Figure 2). Contrary to our hypothesis, CSC enhanced inhibitory neurotransmission, and rAIH had no additional affect. Since these electrophysiology results are in contrast to our immunofluorescence results, we question whether the technique used (i.e., intrathecal injections) were sensitive enough to detect differences in inhibitory neurotransmission in the phrenic motor pool.

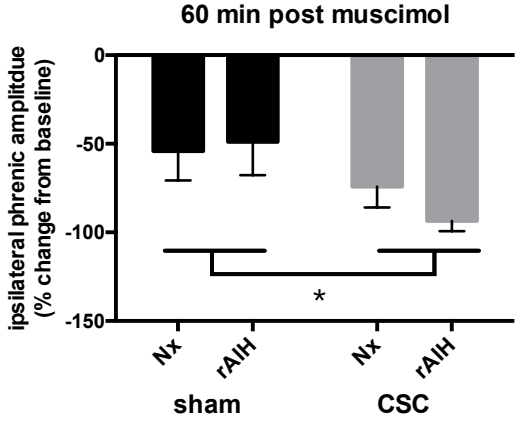

Figure 2: Phrenic burst amplitude ipsilateral to sham or CSC injury 60 min following intrathecal muscimol (7.5 mM). In all groups, phrenic burst amplitude decreases following muscimol injections, suggesting strong $GABA_A$ receptor-mediated inhibition. Rats receiving CSC had a increased phrenic responses to muscimol, suggesting that CSC enhances inhibitory neurotransmission, which is contrary to our hypothesis.

Subtask 2d: Histological verification of injury for all rats in task 3.

Current Status: Analysis underway. Will be completed by 9/1/16. We will histologically describe the CSC injury in rats studied in Subtask 2b and 2c to determine if variability in the extent of injury accounts for variability in NKCC1/KCC2 expression and the electrophysiological response to $GABA_A$ agonists.

Task 4: Analyze data and draft manuscript describing the effect of C4 cervical spinal contusions (CSC) on NKCC1/KCC2 balance and GABAA receptor-induced inhibition of phrenic motor output.

Current Status: Data analyzed, manuscript in progress.

Specific Aim 1c: CSC-induced attenuation of chloride-dependent synaptic inhibition requires PKCζ.

Task 5: Quantify changes in membrane NKCC1 and KCC2 after CSC in rats with and without PKCζ knockdown in phrenic motor neurons.

Current Status: Since CSC did not result in an attenuation in chloride-dependent synaptic inhibition (Task 3, subtask 3c, Figure 2), we did not complete this task.

Task 6: Quantify GABAA receptor-induced inhibition of phrenic motor output following cervical contusion injuries in rats with PKCζ knockdown in phrenic motor neurons.

Current Status: Since CSC did not result in an attenuation in chloride-dependent synaptic inhibition (Task 3, subtask 3c, Figure 2), we did not complete this task.

Task 7: Quantify ventilation following cervical contusion in rats with PKCζ knockdown in phrenic motor neurons.

Subtask 7a: Begin intrapleural siRNA injections 3 days prior to surgery.

Current Status: Have completed 3/8 in each group. Will be completed by 9/1/16

Subtask 7b: Perform contusion injuries and sham surgeries.

Current Status: Have completed 3/8 in each group. Will be completed by 9/1/16

Subtask 7c: Perform plethysmography on multiple days post-surgery (beginning day before surgery and continuing for 5 wks).

Current Status: Have begun studies on 3/8 in each group. Will be completed by 9/1/16. Results are detailed below:

In the last reporting period, we began studies investigating the impact of spinal PKCζ down-regulation on spontaneous recovery of diaphragm activity following CSC. Six rats were implanted with radio-telemetric electrodes in the right and left hemidiaphragm to measure diaphragm EMG activity before and 3 days following CSC in rats receiving intrapleural injections of non-targeting siRNAs or siRNAs targeting PKCζ. Tidal volume and breathing frequency were also measured in a plethysmograph before and 3 days following CSC in rats receiving intrapleural injections of non-targeting siRNAs or siRNAs targeting PKCζ (Figures 3 & 4). Our preliminary data suggest that during maximum chemoreceptor stimulation: 1) a spontaneous recovery of diaphragm EMG activity is apparent within 3 days post-CSC (n=3), 2) spinal PKCζ downregulation blocks spontaneous diaphragm EMG recovery (n=2; note—one rat exhibited enhanced activity post-CSC and siPKCζ; this rat is not included in the graph below since we suspect issues with diaphragm EMG implantation). Analysis of spontaneous recovery at 5 weeks post-CSC in these groups is underway. Further studies to complete this Aim are planned and will be completed by 9/1/16.

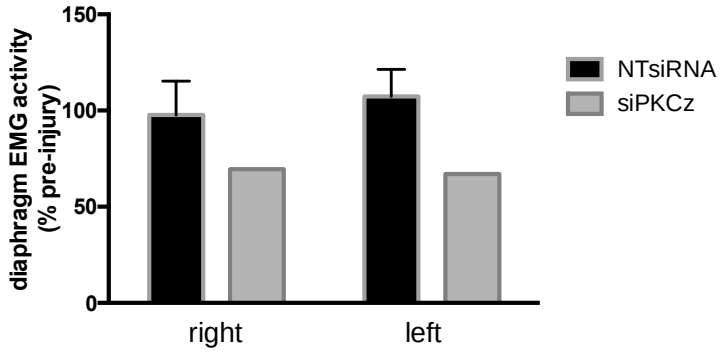

Figure 3. Diaphragm EMG activity under maximum chemoreceptor stimulation 3 days following cervical spinal contusion (CSC) in rats receiving control injections of a non-targeting siRNA (NTsiRNA) or siRNAs targeting PKCζ (siPKCζ). Rats injected with NTsiRNA exhibited a full recovery of diaphragm EMG activity 3 days following CSC (n=3). Rats injected with siPKCζ exhibited impaired diaphragm EMG activity 3 days following CSC (n=2), suggesting that spontaneous recovery of diaphragm activity post-CSC requires spinal PKCζ.

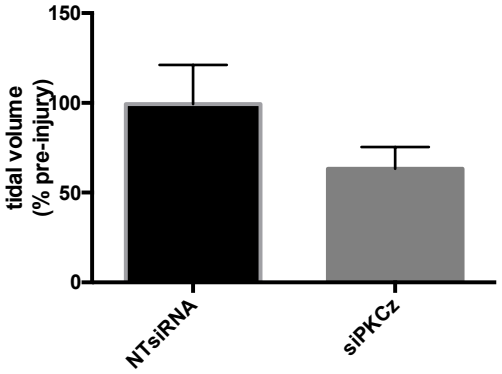

Figure 4. Tidal volume in normoxia 3 days following cervical spinal contusion (CSC) in rats receiving control injections of a non-targeting siRNA (NTsiRNA) or siRNAs targeting PKCζ (siPKCζ). Rats injected with NTsiRNA exhibited a full recovery of tidal volume 3 days following CSC (n=3). Rats injected with siPKCζ exhibited impaired tidal volume 3 days following CSC (n=2), suggesting that spontaneous recovery of breathing post-CSC requires spinal PKCζ.

Subtask 7d: Histological verification of injury for all rats in task 7.

Current Status: Will be completed during NCE year, by 9/1/16

Task 8: Draft manuscript concerning role of PKCζ in spontaneous shifts in NKCC1/KCC2 balance, degraded synaptic inhibition of phrenic motor output and spontaneous functional recovery of breathing following cervical contusions.

Current Status: Will be completed during NCE year, by 9/1/16

Specific Aim 2c: Test the hypothesis that rAIH-induced normalization of chloride-dependent synaptic inhibition requires TrkB activity.

Current Status: Since rAIH had no effect on NKCC1/KCC2 balance or inhibitory neurotransmission (Task 3, Figures 1 and 2), we did not complete this task.

KEY ACCOMPLISHMENTS TO DATE

Our work has resulted in two major findings. First, similar to lumbar motor neuron pools (Boulenguez et al., 2010; Cramer et al.,2008), NKCC1/KCC2 balance in phrenic motor neurons shifts following spinal injury in way that would be expected to enhance excitatory neurotransmission. Unfortunately, our electrophysiological analysis did not support degraded inhibitory neurotransmission (in fact, it suggested the opposite); we suspect that this result is due to delivering the $GABA_A$ agonist intrathecally *versus* directly into the phrenic motor pool. Although our hypothesis that rAIH normalizes inhibitory neurotransmission (while maintaining enhanced excitatory neurotransmission) also did not pan out, we suspect that the timing of rAIH treatment in our studies was not optimal. Indeed, recent data from the Mitchell laboratory suggests that in the weeks following spinal injury, plasticity following rAIH shifts from a predominately adenosinergic to a predominately serotonergic mechanism. Thus, in future studies, rAIH treatment should be delayed to better correspond with the time of maximal serotonergic function. Regardless, our data are consistent with the hypothesis that following spinal injury, an endogenous compensatory mechanism is elicited in phrenic motor neurons that may act to preserve respiratory function.

A second major finding is that spinal PKCζ activity may underlie the spontaneous recovery of diaphragm EMG activity and breathing capacity that naturally develops in some human patients and rodent models following spinal cord injury (Goshgarian, 2003; Raineteau and Schwab, 2001). Indeed, we found that rats with a knockdown of spinal PKCζ lacked the normal compensatory increases in diaphragm EMG activity and breathing capacity following CSC; if these results are upheld in remaining rats, this will be the first report to our knowledge of any molecule underlying spontaneous plasticity following spinal injury. This striking finding may have profound implications for the development of novel therapeutic strategies to treat spinally injured patients in which these endogenous compensatory mechanisms fail. We anticipate completing this study during our NCE year.

Our work on this project has resulted in two abstracts (listed below), and a manuscript describing the impact of CSC on NKCC1/KCC2 balance is currently being drafted.

PROBLEMS

Dr. Mitchell's departure from the University of Wisconsin to the University of Florida put us behind schedule last year, leading us to request a no cost extension. Dr. Mitchell's Florida laboratory is now fully operational, and studies are proceeding as planned.

CONCLUSIONS

We made good progress in accordance with our experimental plan, although we experienced delays related to Dr. Mitchell's move to University of Florida and unexpected experimental findings. We completed our analyses of GABA receptor-induced phrenic inhibition and phrenic motor neuron NKCC1/KCC2 expression following CSC. rAIH had little, if any, impact on our results. This lack of effect may be due to the timing of rAIH administration due to recent discoveries in the Mitchell laboratory pertaining to shifts in the mechanism of rAIH effects on phrenic motor neurons with time post cervical spinal injury. We also obtained promising preliminary data suggesting that spinal PKCζ activity is necessary for spontaneous recovery of phrenic motor output post-CSC and will complete these studies with the remainder of our limited funds. Thus, major goals for the rest of this year are to complete PKCζ studies and to prepare a manuscript to publish findings of the immunofluorescence studies. These results may be significant for patients with spinal injury since they suggest a new cellular target for future therapeutic development (PKCζ). Our research directly targets the goal of improving breathing capacity and/or coordination in patients with cervical SCI.

PUBLICATIONS, ABSTRACTS AND PRESENTATIONS:

L Allen, K Braegelmann, S Fischer, L Sullivan, S Springborn, E Kopp, TL Baker-Herman, and GS Mitchell (2015). Cervical Spinal Contusion Injury Alters Membrane Expression of NKCC1 and KCC2 in Phrenic Motor Neurons: Impact of Repetitive Acute Intermittent Hypoxia. FASEB abstracts

L Allen, YB Seven, T Baker and GS Mitchell (2016) Cervical Spinal Contusion Alters NKCC1 and KCC2 Expression in Phrenic Motor Neurons. FASEB abstracts (manuscript in preparation).

INVENTIONS, PATENTS AND LICENSES: None

REPORTABLE OUTCOMES: None, pending completion of our studies.

OTHER ACHIEVEMENTS: None

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Cramer SW, Baggott C, Cain J, Tilghman J, Allcock B, Miranpuri G, Rajpal S, Sun D, Resnick D (2008). The role of cation-dependent chloride transporters in neuropathic pain following spinal cord injury. Mol Pain. 4:36.

Goshgarian HG (2003). The crossed phrenic phenomenon: a model for plasticity in the respiratory pathways following spinal cord injury. J Appl Physiol. 94(2):795-810.

Raineteau O and Schwab ME (2001). Plasticity of motor systems after incomplete spinal cord injury. Nat Rev Neurosci. 2(4):262-73.

APPENDICES: None